AMSU CALIBRATION

1. Introduction

In early 1998, NOAA will launch a new generation of total-power microwave radiometers aboard its NOAA-K, L, M, and N series of Polar-orbiting Operational Environmental Satellites (POES). The instrument called the Advanced Microwave Sounding Unit (AMSU) contains 20 channels and is comprised of two major components, AMSU-A and AMSU-B. The AMSU-A component contains two modules, AMSU-A1 and -A2. Figure 1 shows the various modules along with their channel frequencies and Instantaneous Field Of View (IFOV) at nadir. In total, AMSU-A contains fifteen channels, details of which are described in [1].

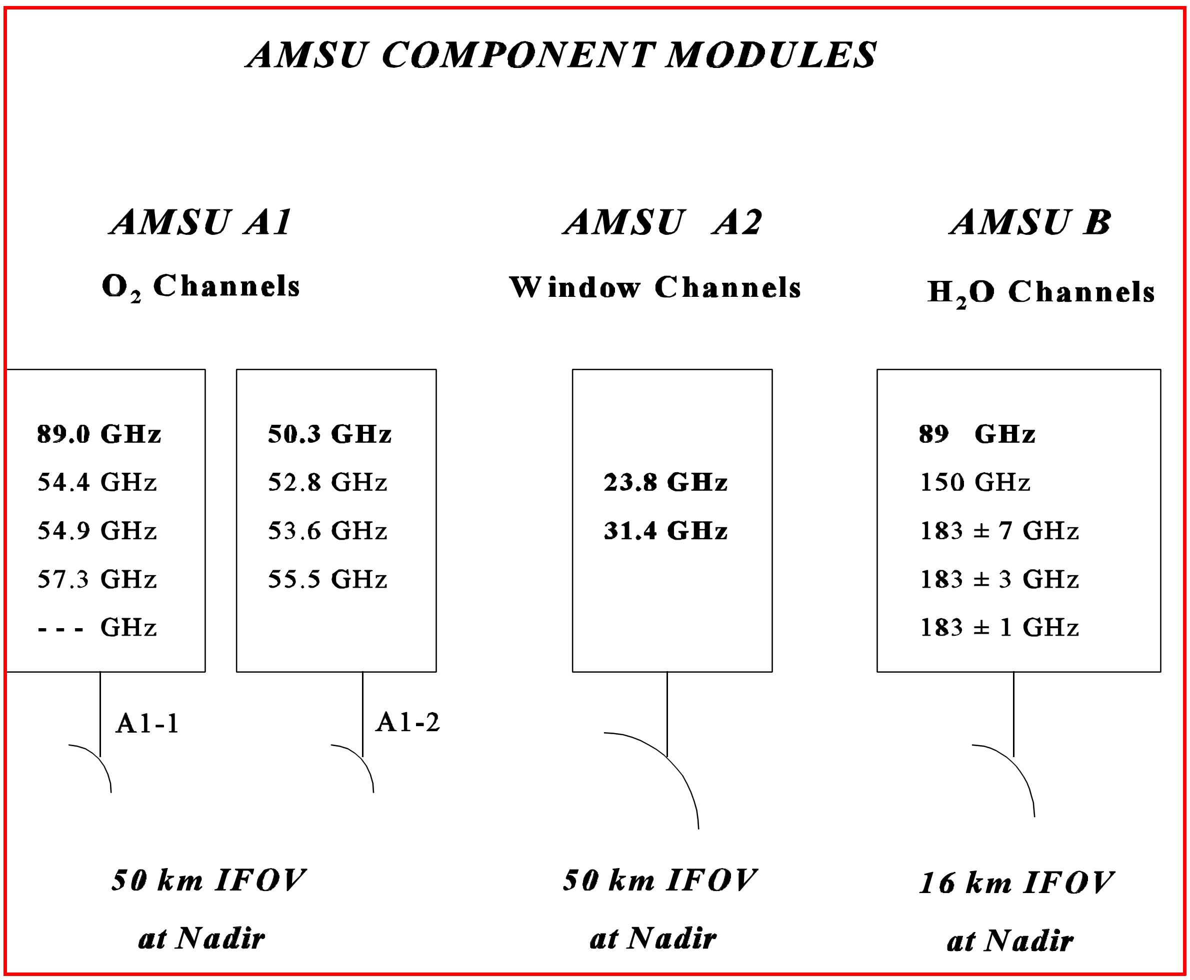

Figure 1. AMSU components, showing the channel center frequencies and IFOV at nadir. The frequencies in bold denote channels which will be used in the NESDIS operations to produce surface and precipitation climate products.

The AMSU-A1 module uses two separate antenna-radiometer systems (A1-1 and A1-2) to provide twelve channels in the 50 to 60 GHz oxygen band (see Fig. 1) for retrieving the atmospheric temperature profile from the Earth's surface to about 42 kilometers (or 2 mb). The AMSU-A1 module also contains a channel at 89 GHz, while AMSU-A2 has two channels at 23.8 and 31.4 GHz to identify precipitation and correct for surface emissivity, atmospheric liquid water, and water vapor effects. These window channels are also used to derive rain rate, sea ice concentration, and snow cover for example.

Table 1 lists some of the main AMSU channel characteristics, which include the channel central frequencies, number of bands, bandwidth, and radiometric temperature sensitivity (or NEΔT) for each channel. Details of these quantities are given in [1] and [2]. The main beam and cross-polarization beam efficiencies as well as beamwidths for individual channels were calculated using measured AMSU antenna patterns [3,4] and are also listed in Table 1. Each of the AMSU-A antenna systems has a nominal IFOV of 3.3^{o} at the half-power points and scans across the Earth within a maximum angle of ±48° (beam centers) from the nadir direction. The antenna reflectors rotate one complete revolution every 8 seconds, during which 30 Earth scene resolution cells (also referred to as beam positions, each separated by 3^{o}20') will be sampled in a stepped-scan fashion. Onboard calibration is obtained by viewing the cold space cosmic background temperature (2.7 K) and an internal blackbody target every 8 seconds for each scan line. Beam positions 1 and 30 are the extreme scan positions of the Earth views, while beam positions 15 and 16 are at 1^{o}40' and -1^{o}40' from the nadir direction, respectively.

The second component AMSU-B has five channels with two channels centered nominally at 89 GHz

Table 1. Channel characteristics and specifications of AMSU-A2 PFM, AMSU-A1 FM1, and AMSU-B for NOAA-K.

Channel Number	Channel Frequency (MHz)	Number of Bands	Measured 3-dB Bandw (MHz)	NEΔT Spec. (K)	Measred (K)	Main Beam Efficiency	Cross Polarizatio Beam Effici	3-dB Beamwidth (deg.) **	Polarizatio at nadir	Remarks
	AMSU-A :									
1	23800	1	251.02	0.30	0.211	95.39%	1.57%	3.53	V	A2/PFM
2	31400	1	161.20	0.30	0.265	97.14%	1.23%	3.41	V	"
3	50300	1	161.14	0.40	0.219	95.39%	2.24%	3.76	V	A1-2/FM1
4	52800	1	380.52	0.25	0.143	95.50%	1.21%	3.72	V	"
5	53596 ± 115	2	168.20	0.25	0.148	95.55%	1.38%	3.70	H	"
6	54400	1	380.54	0.25	0.154	95.08%	1.65%	3.68	H	A1-1/FM1
7	54940	1	380.56	0.25	0.132	94.79%	1.47%	3.61	V	"
8	55500	1	310.34	0.25	0.141	95.05%	1.44%	3.63	H	A1-2/FM1
9	fo = 57290.344	1	310.42	0.25	0.236	95.91%	1.29%	3.51	H	A1-1/FM1
10	fo ± 217	2	76.58	0.40	0.250	"	"	"	H	"
11	fo ± 322.2 ± 48	4	35.11	0.40	0.280	"	"	"	H	"
12	fo ± 322.2 ± 22	4	15.29	0.60	0.400	"	"	"	H	"
13	fo ± 322.2 ± 10	4	7.93	0.80	0.539	"	"	"	H	"
14	fo ± 322.2 ± 4.5	4	2.94	1.20	0.914	"	"	"	H	"
15	89000	1	1998.98	0.50	0.166	97.79%	1.38%	3.80	V	"
	** Specification is required to have 3.3 degrees ± 10% for all channels.									
	AMSU-B :									
16	89000	2	1000	1.0	0.37	94.4%	0.2%	1.12	V	PFM
17	150000	2	1000	1.0	0.84	95.1%	1.4%	1.08	V	PFM
18	183310 ± 1000	2	500	1.0	1.06				V	PFM
19	183310 ± 3000	2	1000	1.0	0.70	96.9%	0.8%	1.12	V	PFM
20	183310 ± 7000	2	2000	1.2	0.60				V	PFM

and 150 GHz, and the other three centered around the 183.31 GHz water vapor line with double-sideband centers located at 183.31±1, ±3, and ±7 GHZ, respectively. AMSU-B has a FOV of 1.1 degrees ±10%, and once every 8/3 seconds it measures 90 Earth views, space view, and internal blackbody target view. The AMSU-B, is provided by the U. K. Meteorological Office for humidity sounding, and has been described in [2].

2. *Calibration*

The calibration procedures for the AMSU-A and AMSU-B are the same, except a few minor differences to allow for the separate antenna systems. Table 2 lists the main differences between the AMSU-A and AMSU-B procedures. Radiances for both AMSU-A and -B Earth views are derived from the measured counts and the calibration coefficients inferred from the internal blackbody and space view data. Both AMSU-A and AMSU-B were tested and calibrated in thermal vacuum (TV) chambers before launch. Scanings of both instruments are synchronized to an 8-second pulse. Each instrument has four options for the viewing direction of the space view which can be selected by ground command, and one will be chosen immediately after launch.

Table 2. Differences between the AMSU-A and AMSU-B procedures

Items	AMSU-A			AMSU-B	Remarks
	A1-1	A1-2	A2		
Number of PRTs in each warm target	5	5	7	7	Internal black body targets
Number of Earth views per scan line	30	30	30	90	In-orbit
Blackbody and space samples	2	2	2	4	Per scan line
Definition of instrument temperature	RF Shelf A1-1	RF Shelf A1-2	RF Shelf A2	Mixer temp. of Ch. 18-20	Available in housekeeping
Backup of instrument temperature	RF Mux A1-1	RF Mux A1-2	RF Mux A2	Mixer temp of Ch. 16	See Note 1.
Secondary PLLO	Ch. 9-14	NO	NO	NO	Backup PLLO

Note 1: These temperatures (available in the housekeeping data) will be used as backups if the primary ones fail.

The AMSU-A1-1 also has redundant phase locked loop oscillators (PLLO) for Channels 9-14, which will be used as backups if the primary PLLO fails.

2.1. *Blackbody Temperature*

The physical temperatures of the internal blackbody targets are measured by Platinum Resistance Thermometers (PRTs). The number of PRTs used to measure the physical temperatures of the internal blackbody targets in each antenna system is given in Table 2. These PRTs, which were calibrated by individual manufacturers against 'standard' ones traceable to NIST, measure temperatures of the internal blackbody targets with an accuracy of ±0.1K. The outputs to the telemetry are PRT counts, which must be converted to PRT temperatures. The normal approach for deriving the PRT temperatures from counts is a two-step process, in which the resistance of each PRT (in ohms) is computed by a count-to-resistance look-up table provided by its manufacturer. Then, the individual PRT temperature (in degrees) is obtained from an analytic PRT equation. However, this can be compressed to a single step with negligible errors.

This single step process, which will be used with the NOAA-KLM satellites, computes the PRT temperatures directly from the PRT counts, using a polynomial of the form

$$T_k = \sum_{j=0}^{3} f_{kj} C_k^j \tag{1}$$

where T_k and C_k represent the temperature and count of the PRT k. The coefficients, f_{kj}, will be provided for each PRT. Equation 1 is also used for other housekeeping temperature sensors, such as the mixers, the IF amplifiers and the local oscillators.

The mean blackbody temperature, T_W is a weighted average of all PRT temperatures:

$$T_w = \frac{\sum_{k=1}^{m} w_k T_k}{\sum_{k=1}^{m} w_k} + \Delta T_w \tag{2}$$

where m represents the number of PRTs for each antenna system as listed in Table 2. The w_k is the weight assigned to each PRT and ΔT_W is the warm load correction factor for each channel derived from the TV test data for three instrument temperatures (low, nominal, and high). Values for ΔT_W will be provided for each instrument. For AMSU-A1-1, ΔT_W values for both PLLO#1 and PLLO#2 will be provided. The w_k value, which equals 1 (0) if the PRT is determined good (bad) before launch, will be provided for each flight model. If any of the PRT temperatures, T_k, differs by more than 0.2K from its value in the previous scan line, then the T_k should be omitted from the average in Equation 2.

Similarly, a cold space temperature correction, ΔT_c, is also provided for processing the in-orbit data. This is due to the fact that the space view is contaminated by radiation which originates from the spacecraft platform and the Earth's limb. Thus, the effective cold space temperature is given by,

$$T_c = 2.73 + \Delta T_c \tag{3}$$

where 2.73K is the cosmic background brightness temperature. The ΔT_c , which represents the contribution from the antenna side lobe interference with the Earth limb and spacecraft, is estimated initially for individual channels, but its optimal value will be determined from post-launch data analysis.

2.2. *Calibration Counts*

For each scan, the blackbody counts C_w are the averages of two (four) samples of the internal black body in AMSU-A (AMSU-B). If any two samples differ by more than a preset limit of blackbody count variation ΔC_w (the initial limit is set to 3σ, where the standard deviation, σ, is calculated from the pre-launch calibration data C_w for each channel), the data in the scan should not be used.

Similarly, the space counts C_c are the average of two (four) samples of the space view for AMSU-A (AMSU-B). If any two space view samples differ by more than the preset limit, the data in the scan should be excluded.

To reduce noise in the calibrations, the C_x (where x = w or c) for each scan line will be convoluted over several neighboring scan lines according to a weighting function:

$$\overline{C_x} = \frac{1}{n+1}\left[\sum_{i=-n}^{n}\left(1-\frac{|i|}{n+1}\right)C_x(t_i)\right], \quad \text{counts} \tag{4}$$

where t_i (when $I \neq 0$) is the time of the scan line just before or after the current scan line. If t_0 is the time of the current scan line, one can write $t_i = t_0 + i\Delta t$, where Δt = 8 seconds for AMSU-A and 8/3 seconds for AMSU-B. The 2n+1 values are equally distributed about the scan line to be calibrated. For both AMSU-A and AMSU-B, the value of n=3 is recommended.

For the first and the last three scan lines in a file, the convolution of C_x should be omitted and the counts C_x from the individual scan line will replace $\overline{C_x}$. In the case of missing scan lines in the 2n+1 interval, any one of the remaining scan lines can be selected to replace the missing one(s) in the convolution of C_x. If the gap of missing scans is larger than 2n+1 (i.e., 7), the convolution process must be terminated at the beginning of the gap and starts anew at the end of the gap.

2.3. ***Earth View Radiances***

The following calibration algorithm, which takes into account any nonlinear contribution due to an imperfect square law detector, is employed to convert observed Earth-viewing counts to radiances:

$$R_s = R_w + \frac{C_s - \overline{C_w}}{G} + Q \ , \qquad \frac{\mathrm{mW}}{\mathrm{m}^2\mathrm{-sr-cm}^{-1}} \tag{5}$$

where R_s is the scene radiance and R_w and R_c are the Planck radiances corresponding to the blackbody temperature T_w and the effective cold space temperature T_c defined in Equations (2) and (3), respectively. The C_s is the radiometric count from the scene (Earth) target. The averaged blackbody and space counts, $\overline{C_w}$ and $\overline{C_c}$, are defined by Equation (4). The channel gain G and the quantity Q, which contains the quadratic contributions, are given by:

$$G = \frac{\overline{C_w} - \overline{C_c}}{R_w - R_c} \ , \qquad \frac{\mathrm{counts}}{\mathrm{mW}/\left(\mathrm{m}^2\mathrm{-sr-cm}^{-1}\right)} \tag{6}$$

and

$$Q = u\,\frac{\left(C_s - \overline{C_w}\right)\left(C_s - \overline{C_c}\right)}{G^2} \ , \qquad \frac{\mathrm{mW}}{\mathrm{m}^2\mathrm{-sr-cm}^{-1}} \tag{7}$$

where u is a predetermined parameter which will be provided at three principal (or backup) instrument temperatures. The u values at other instrument temperatures will be interpolated from these three principal (or backup) values. For channels 9 through 14 (AMSU-A1-1) two sets of the u parameters are provided; one set is for the primary PLLO#1 and the other one for the secondary PLLO#2. The quantity G varies with instrument temperature, which is defined in Table 2.

For channels 19 and 20 of AMSU-B, the monochromatic assumption breaks down (e.g. channel 20 spans 16 GHz) and a band correction with two coefficients (b and c) has to be applied. These coefficients modify T_w to give an effective temperature $T_w^{/}$

$$T_w^{/} = b + c\,T_w \tag{8}$$

which is then used in the Planck function $B(T_w^{/})$ to calculate the radiances for channels 19 and 20. Radiances for all other channels (in both AMSU-A and -B) are computed from $B(T_w)$. The application of Equation (8) is not necessary for the space temperature since the errors in the monochromatic assumption are negligible for such low radiances. For simplification of application, Equation (5) can be rewritten as,

$$R_s = a_0 + a_1 C_s + a_2 C_s^2 \,, \qquad \frac{\text{mW}}{\text{m}^2\text{-sr-cm}^{-1}} \tag{9}$$

The coefficients a_i (where I=0, 1 and 2) can be expressed in terms of R_W, G, $\overline{C_w}$ and $\overline{C_c}$. This can be accomplished by rewriting the right-hand side of Equation (5) in powers of C_S and equates the a_i's to the coefficients of same powers of C_S. The results are:

$$a_0 = R_w - \frac{\overline{C_w}}{G} + u\,\frac{\overline{C_w}\,\overline{C_c}}{G^2} \,, \qquad \frac{\text{mW}}{\text{m}^2\text{-sr-cm}^{-1}} \tag{10}$$

$$a_1 = \frac{1}{G} - u\,\frac{\overline{C_c} + \overline{C_w}}{G^2} \,, \qquad \frac{\text{mW}}{\left(\text{m}^2\text{-sr-cm}^{-1}\right)\text{count}} \tag{11}$$

and

$$a_2 = u\,\frac{1}{G^2} \,, \qquad \frac{\text{mW}}{\left(\text{m}^2\text{-sr-cm}^{-1}\right)\text{count}^2} \tag{12}$$

These calibration coefficients will be calculated for every scan line at each channel and appended to the Level 1b data. With these coefficients, Equation (9) can be used to obtain the scene radiance R_S. It should be noted that the coefficients defined in Equations (10) to 7(12) are functions of instrument temperature. Therefore, they are, in general, not constant and should be recalculated for each scan.

Figure 2 shows a set of samples of the thermal vacuum chamber test data from Channel 6. It shows a good linear relationship between the radiometric counts from the scene target and its

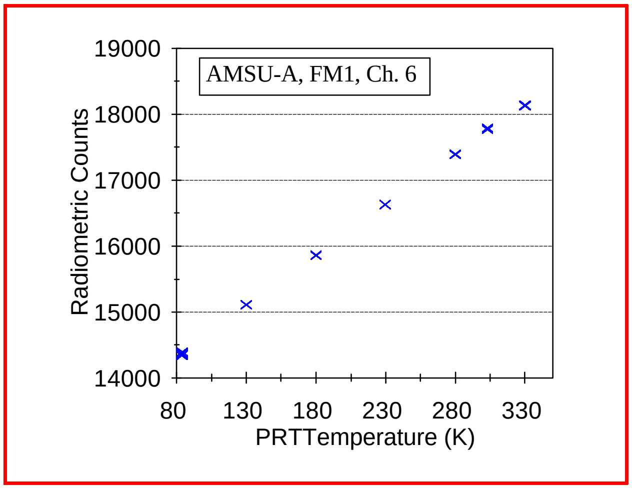

Figure 2. Samples of thermal vacuum chamber test data.

physical temperatures, which were measured by PRTs

Users who prefer brightness temperature instead of radiance, can make the simple conversion,

$$T_s = B^{-1}(R_s) \tag{13}$$

where B^{-1} (R_S) is the inverse of the Planck function for a radiance R_S. The T_S is the corresponding brightness temperature (or radiometric temperature). However, the conversion (Equation 13) is not performed in the NOAA Level 1b data. Note that for AMSU-B channels 19 and 20 the band correction coefficients must also be applied as follows:

$$T_s' = \frac{T_s - b}{c} \tag{14}$$

where T_s' corresponds to the brightness temperature of channel 19 or 20.

3. *ONLINE DOCUMENTATION*

- **The AMSU-A Level 1B Header and Data Formats are on NOAA FTP Server**:

  ftp://ftp2.ncdc.noaa.gov/pub/doc/noaaklm/
  Datasets: klmamsah.xxx & klmamsad.xxx
  where xxx = html, for mosaic browser
  = wp5, for WordPerfect (version 5.0), etc.

- **NOAA-KLM User's Guide (editor K. Kidwell), Section 7.3 AMSU-A and -B**

  http://www2.ncdc.noaa.gov/klm/

References

[1]. Tsan Mo, "Prelaunch Calibration of the Advanced Microwave Sounding Unit-A for NOAA-K," IEEE Trans. Microwave Theory and Techniques, vol. 44, pp. 1460-1469, 1996.

[2]. R. W. Rogers, T. J. Hewison, N. C. Atkinson, and S. J. Stringer, "The radiometric Characterization of AMSU-B," IEEE Trans. Microwave Theory and Techniques, vol. 43, pp. 760-771, 1995.

[3]. Tsan Mo, "AMSU-A Antenna Pattern Corrections," IEEE Trans. Geoscience and Remote Sensing, 1997 submitted for publication.